Advances in
THz Heterodyne Detection Technology

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Outline

- Introduction
- Heterodyne Receivers
- Heterodyne Technology at JPL
  - Mixers
    - Schottky
    - SIS
    - HEB
  - Sources
- Future Challenges
- Concluding remarks

Motivation--THz "Markets"

Space based (NASA/ESA etc):

- Earth Science: Atmosphere and how it changes, cloud dynamics, ozone depletion etc
- Space Science: Study galaxies far away, star formation, star decay etc
- Planetary Science: Planetary atmospheres and the search for volcanic and life signatures, active altitude control for landers etc
- Bioastrophysics: detection of bio-molecules, detection of habitability etc

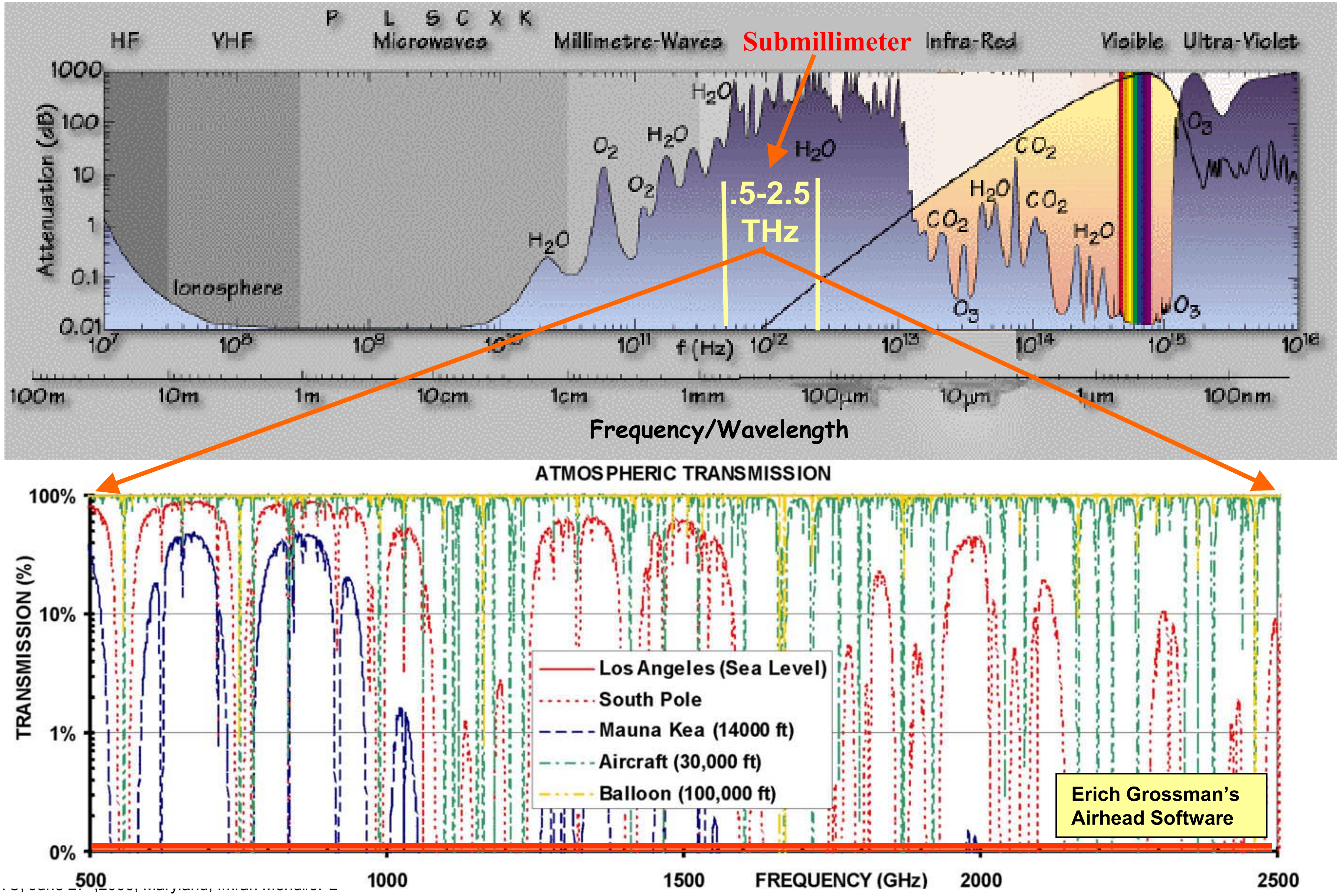
Ground based/Commercial:

THz applications are expanding rapidly and commercial markets are developing: imaging, homeland security etc

To detect the THz energy that is everywhere we need:

THz heterodyne detectors

THz Bands & Atmospheric Transmission



Spacecraft with THz on-board

Space-borne

- SWAS—measurement of water
- UARS-MLS—ozone monitoring
- MIRO—rendezvous with a comet

Earth Orbiter/Sounder

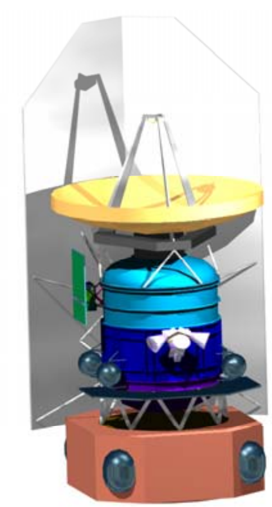
High Altitude Balloon

Airborne Platform (DC8/SOFIA)

Upcomming:

- HIFI on Herschel Space Observatory—Early universe study
- VESPER—Venus Discovery Mission
- SIGNAL—Mars Scout Mission
- SAFIR—Astrophysics mission

Planetary Sounder



Advantages of Heterodyne Receivers

- Heterodyne receivers can easily attain extremely high spectral resolution
  - > For Herschel R ≈ 10^6 and 10^7 ($\Delta v \approx$ 300 m/s and 30 m/s)
  - > FIR or submillimeter grating spectrographs for bolometer detectors would have to be prohibitively large ($l \sim R\lambda$)

- The signals from heterodyne receivers can be reproduced many times and delayed electronically
  - > An extremely useful property when considering interferometers
  - > ESA considering a heterodyne THz space interferometer: ESPRIT
  - > Delay lines for FIR direct detection interferometers must be very large and it is difficult to combine signals from many telescopes

Why High Spectral Resolution?

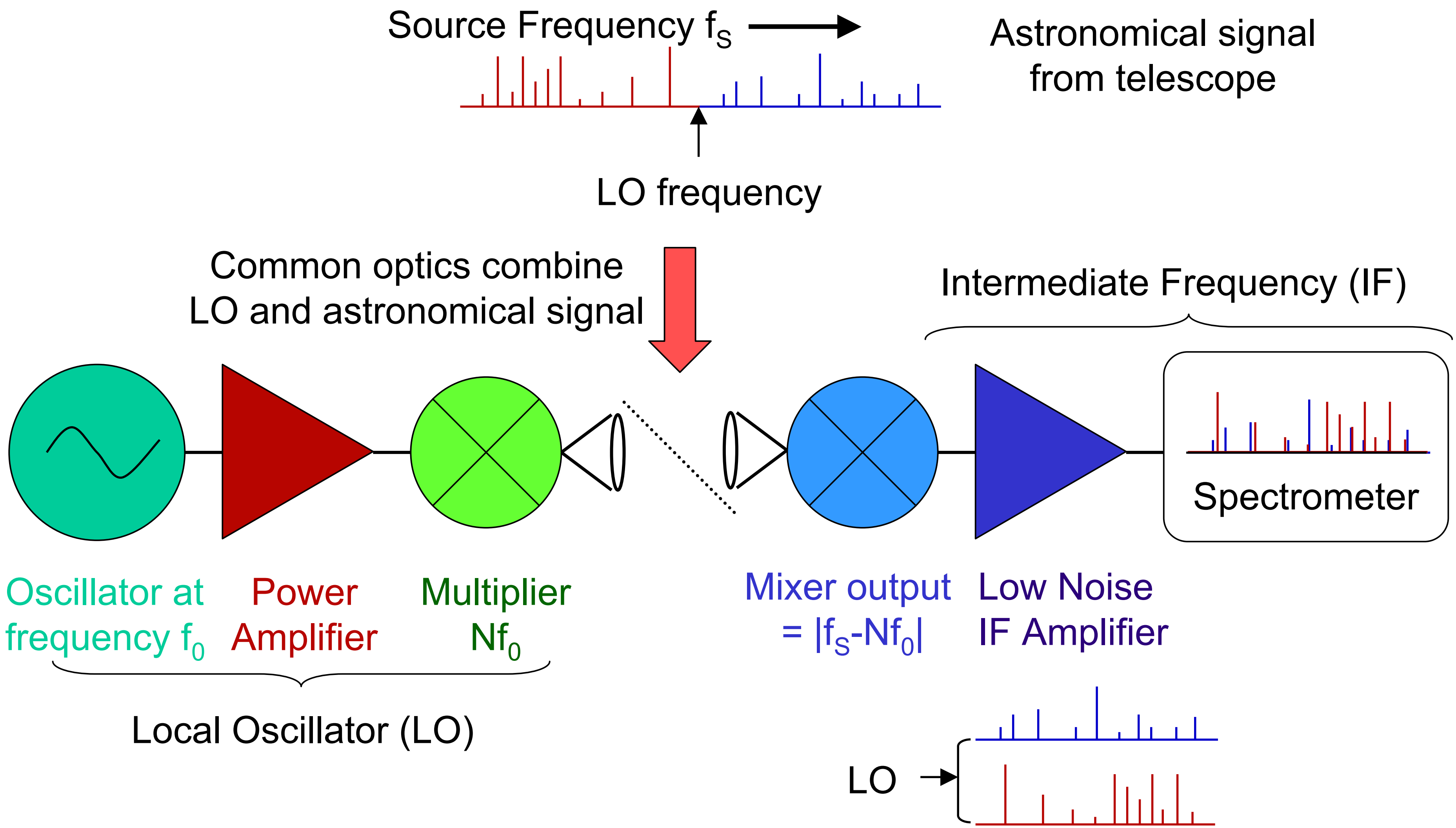
- High spectral resolution is necessary to separate overlapping emission or absorption lines
  - > Spectral lines give us valuable information on the state of the gas
  - > Temperature, density, molecular make-up of the material, local radiation environment, magnetic fields, … can be determined from key spectral lines
  - > Often both emission and absorption occur along the line of sight, so without detailed knowledge of line shape, errors in estimating line strengths will result

Why High Spectral Resolution?

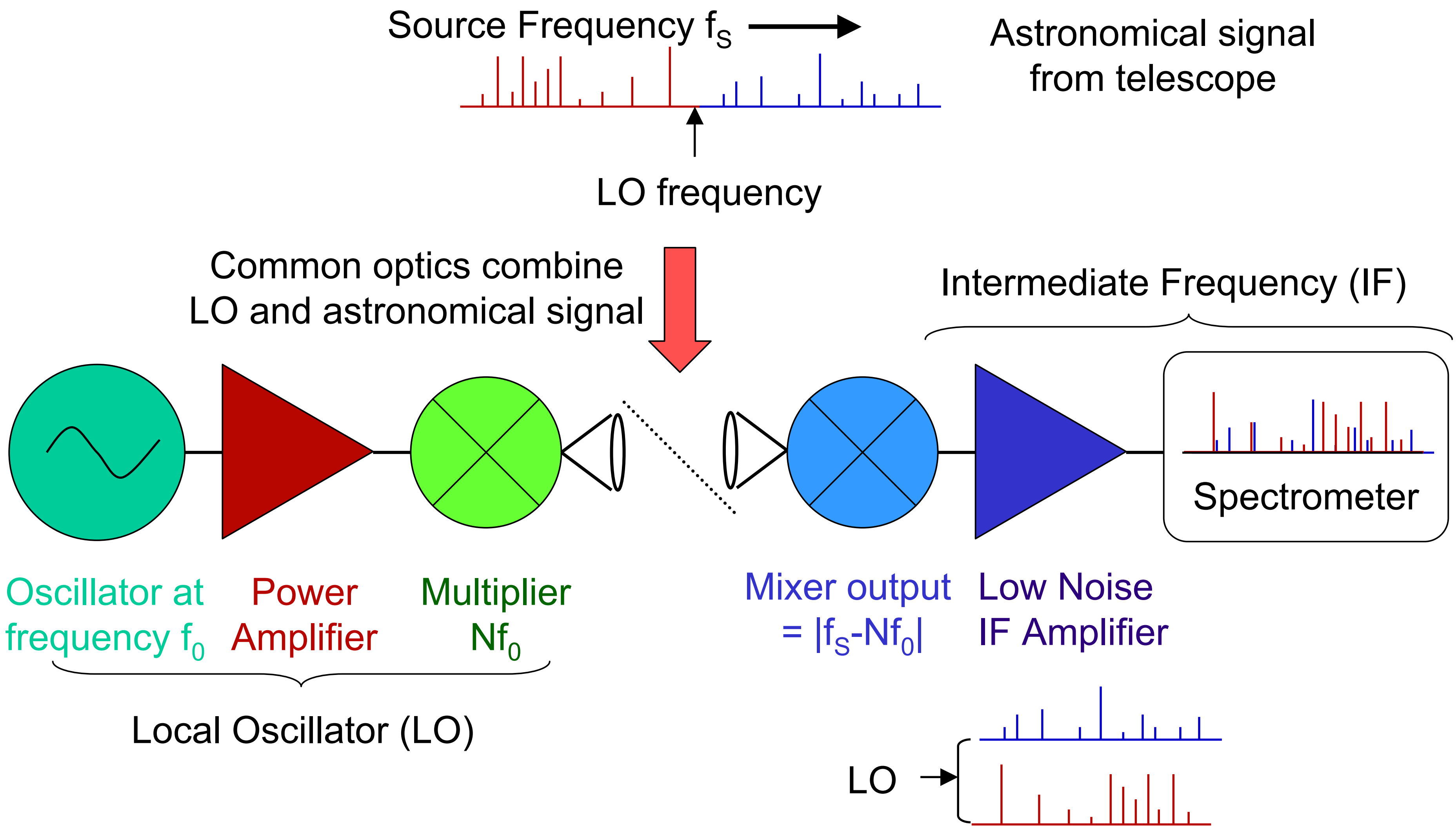
- High spectral resolution is necessary to obtain detailed velocity information from emission and absorption lines
  - > Measuring the motions of gas during processes such as explosions, outflows, accretion,
    etc. is a key ingredient in our understanding of these processes
  - > Velocity allows one to separate line emission & absorption from spatially overlapping regions of the sky
- High spectral resolution allows detection of extremely weak lines
  - > If spectral resolution of spectrograph is much less than the intrinsic line width, then line is "diluted" => loss of sensitivity
  - > Large (pre-biotic) molecules have intrinsic line widths that are extremely narrow and occur in dense, cold regions

- Large molecules can be *uniquely* identified through their line signatures at THz frequencies

High Frequency Heterodyne Functionality

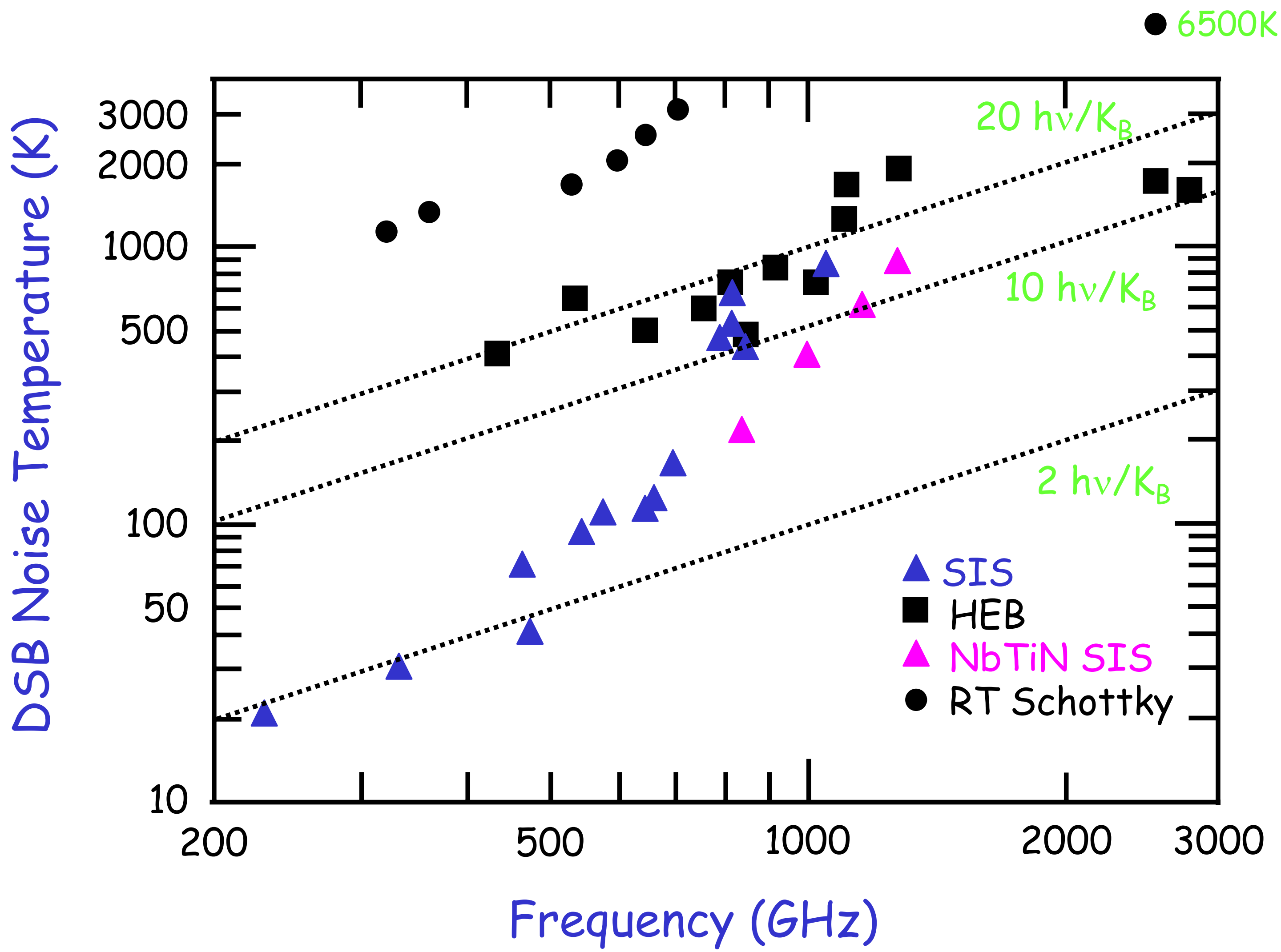


High Frequency Heterodyne Functionality

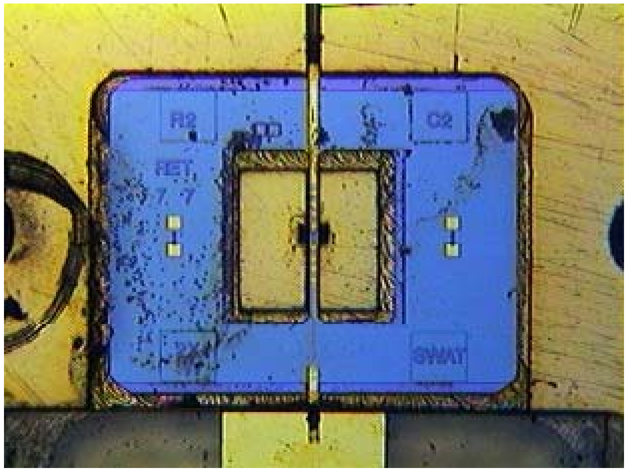


Submillimeter-Wave Mixer Performance

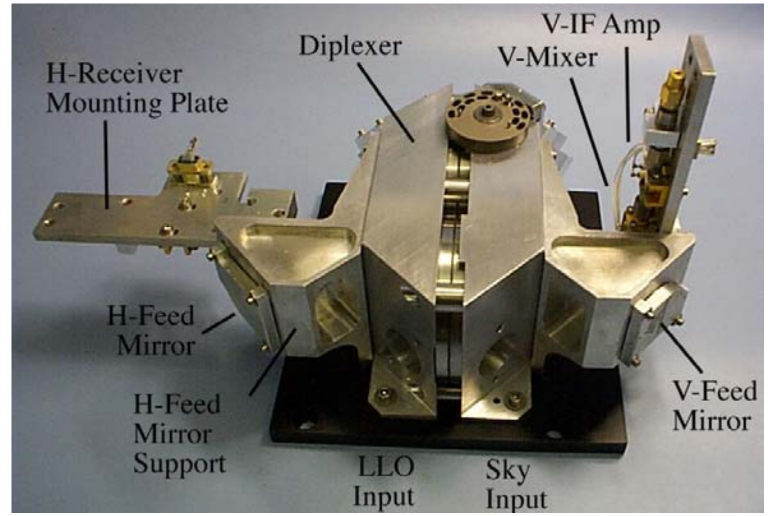
Schottky, SIS and HEB (Hot Electron Bolometers)



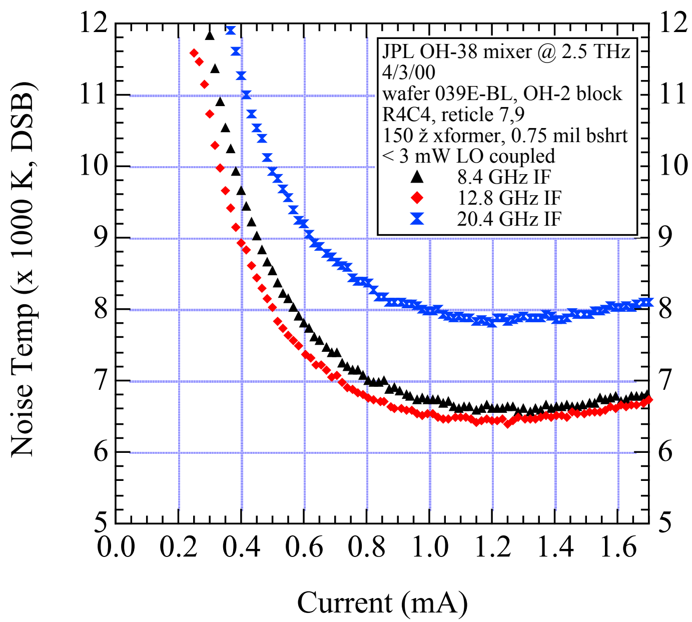
2.5 THz MOMED Mixer/Receiver for EOS-MLS



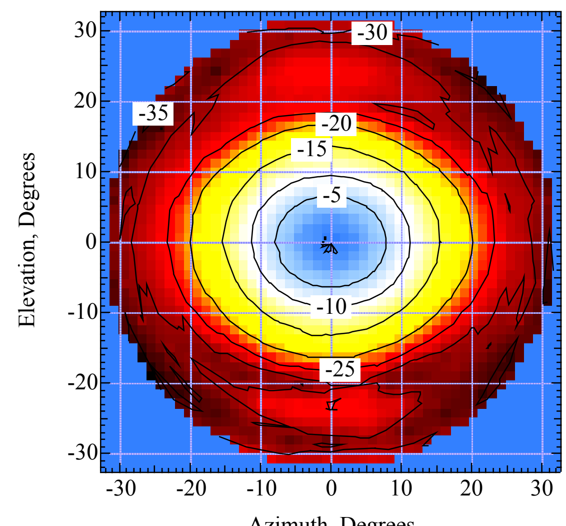
JPL 2.5 THz MOMED mixer chip in waveguide mount



Two channel receiver for 2.5 THz flight application



Receiver performance vs. LO Power at 2.5 THz

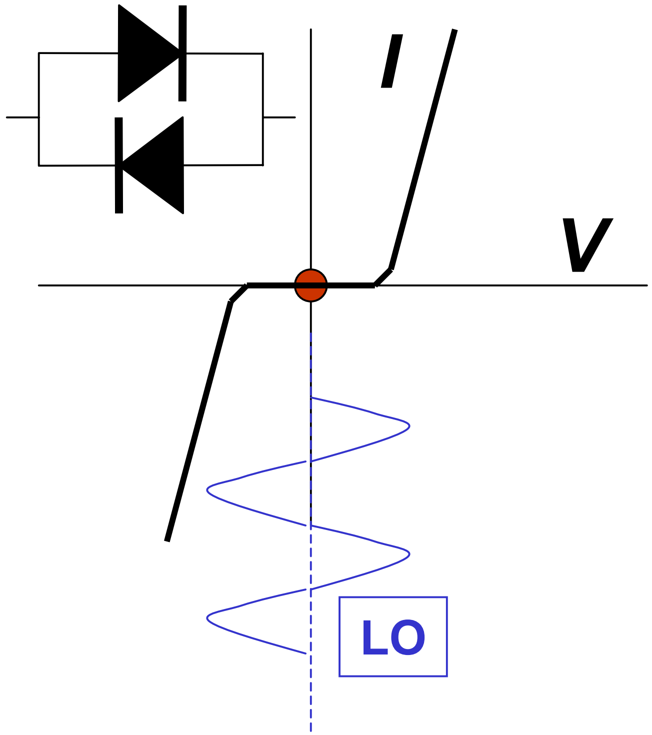


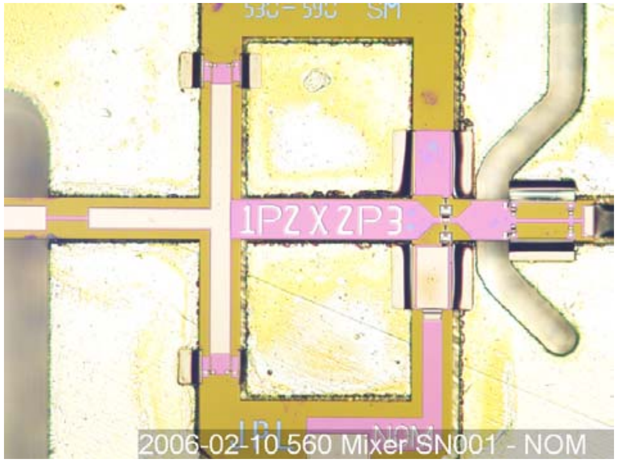
Beam pattern of 2.5 THz dual mode horn

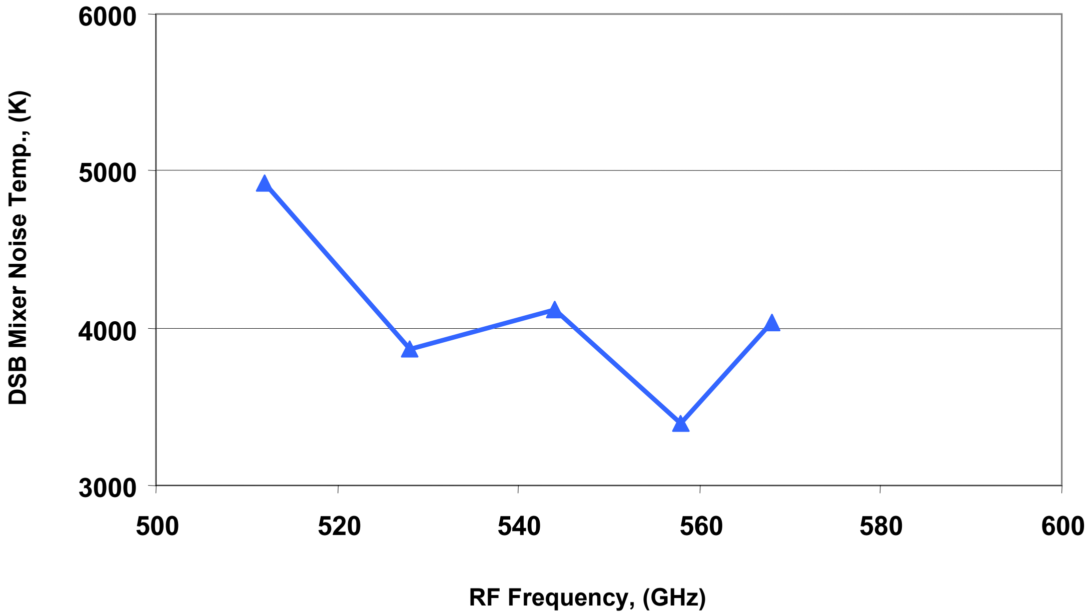
Sponsors:
BSICT, Code Y

Work By:
M. Gaidis, H. Pickett, D. Harding, R. Tsang, T. Crawford, P. Siegel

530-590 GHz Subharmonic biasable Mixer Chip



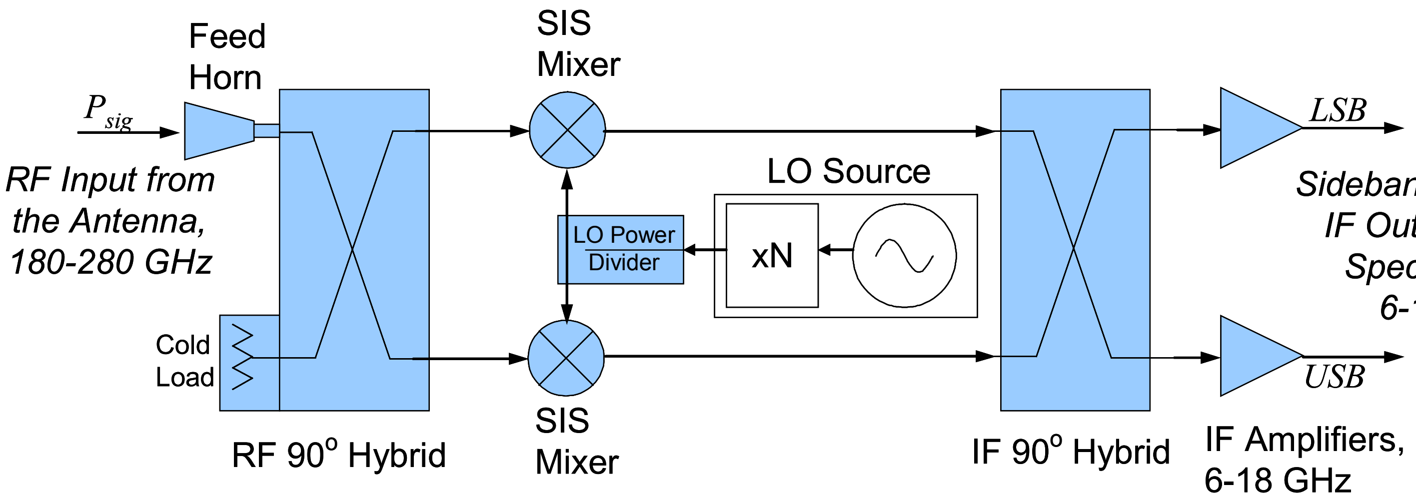




Extend this technology to 4.7 THz

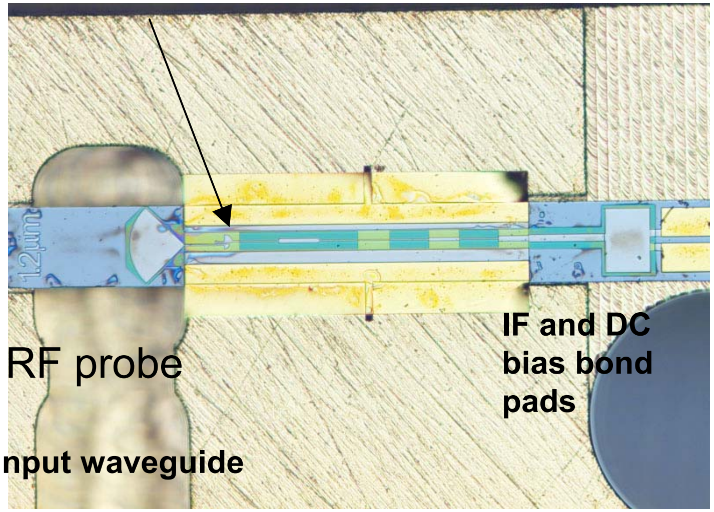
SIS Receivers for CAMEO Microwave Limb Sounder

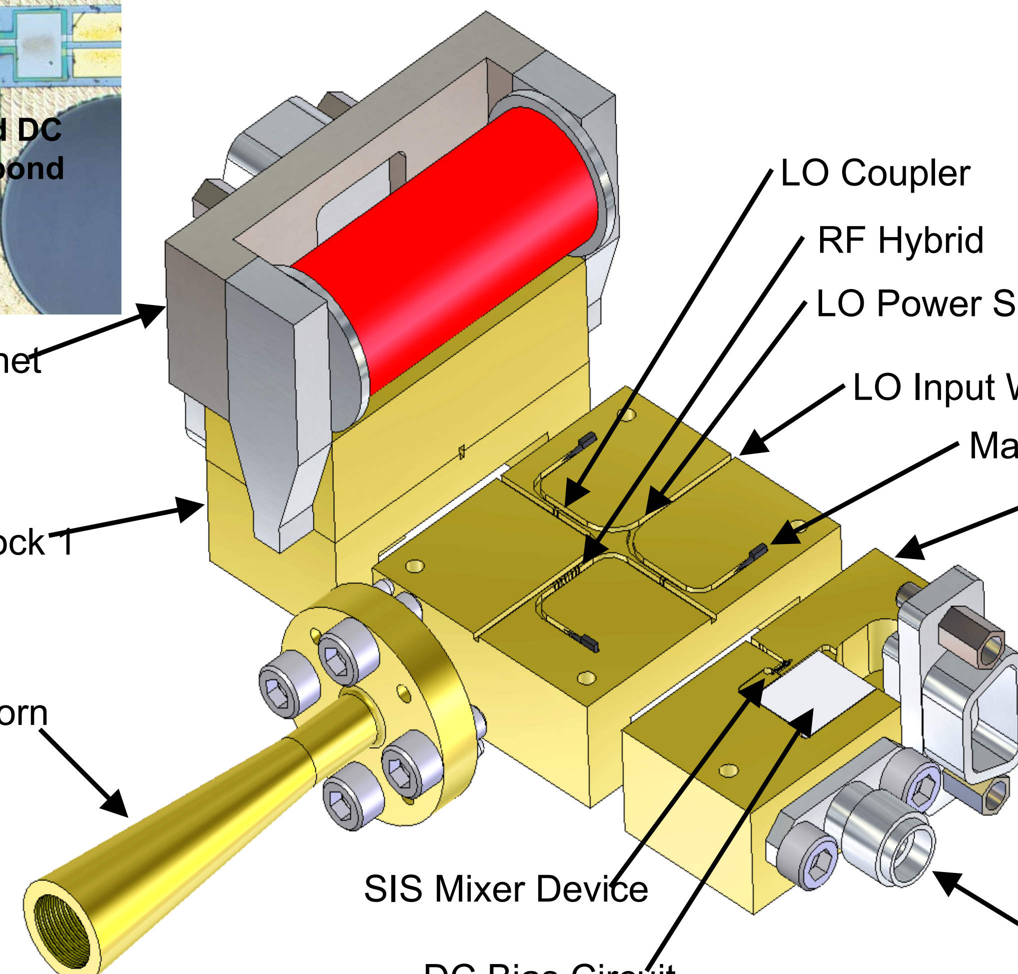
- Niobium SIS junctions with aluminum nitride barriers
- 4.2 K operating temperature
- 180-280 GHz RF band
- 6-18 GHz IF band
- Input noise below 100 K SSB
- Fixed-tuned waveguide circuits
- Corrugated horn input
- Sidebands separated with quadrature hybrids



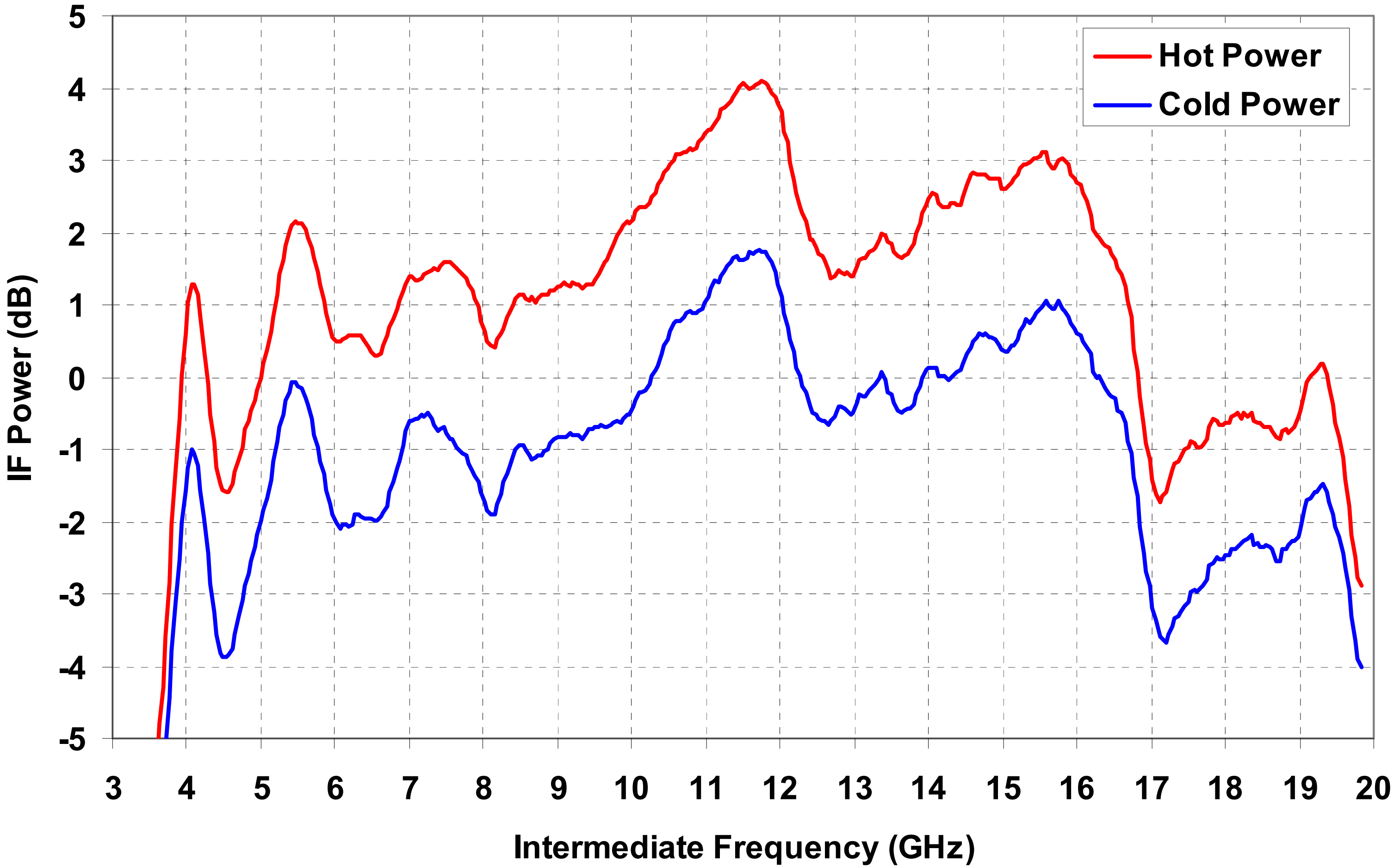
Niobium SIS sideband separating Mixer

Nb/Al-AlNx/Nb SIS junction



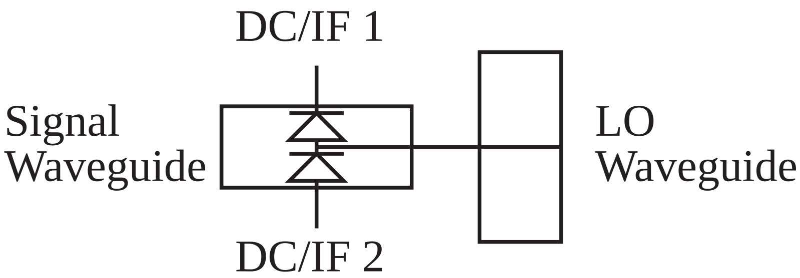


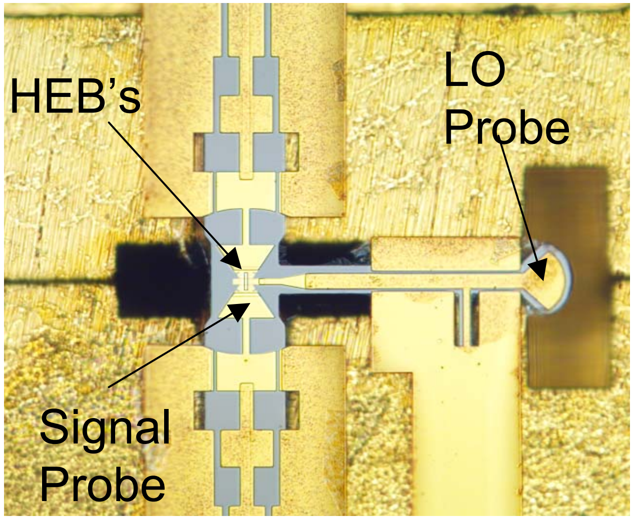
IF Passband

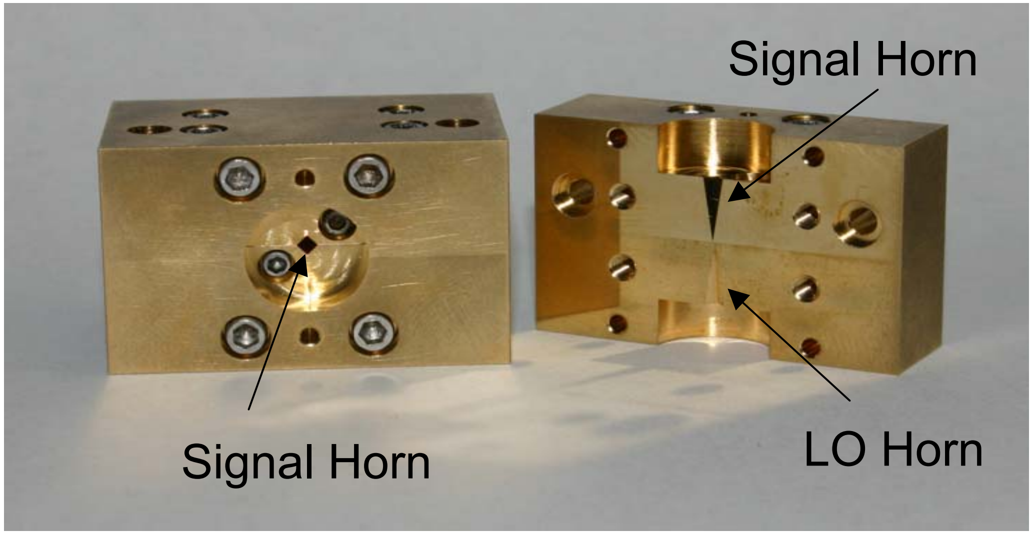


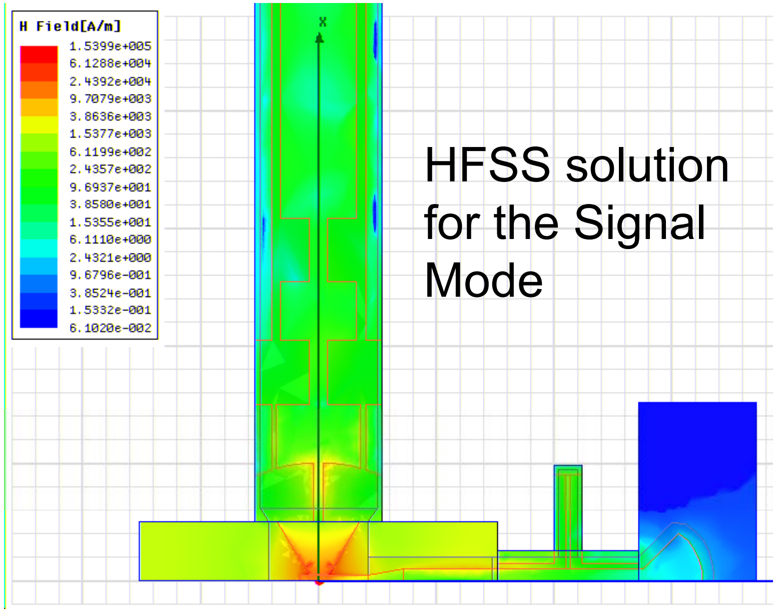
Includes room temperature electronics. Subtracted 0.5 dB/GHz slope.

1.5 THz HEB cross-bar balanced mixer on Silicon-On-Insulator Substrates



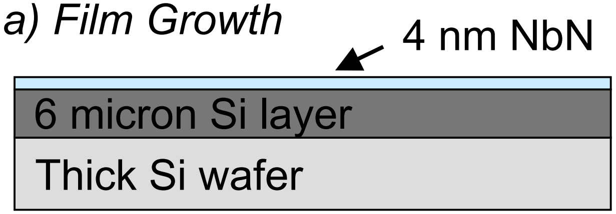




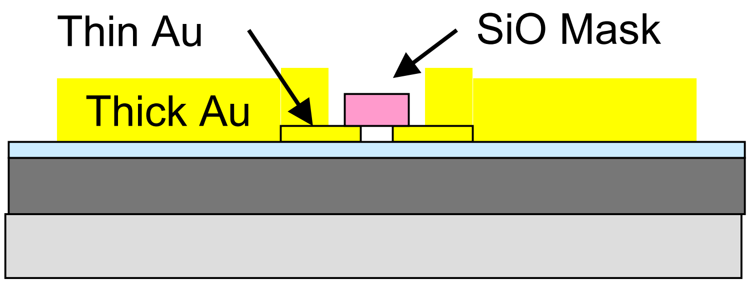


NbN HEB SOI Device Process (Schematic)

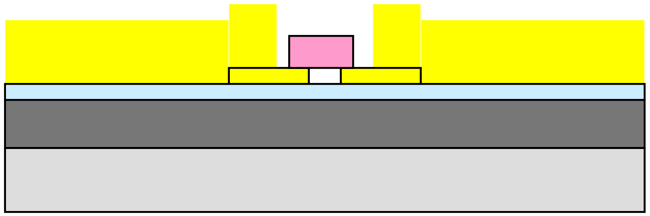
a) Film Growth



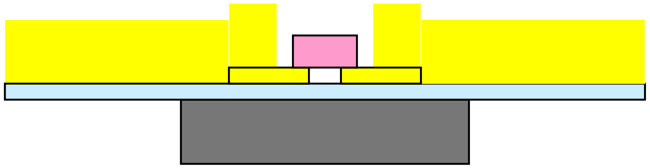
b) Pattern Wiring



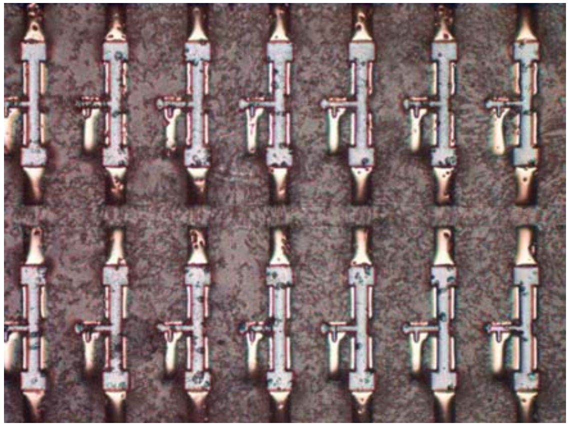
c) Etch the NbN Layer

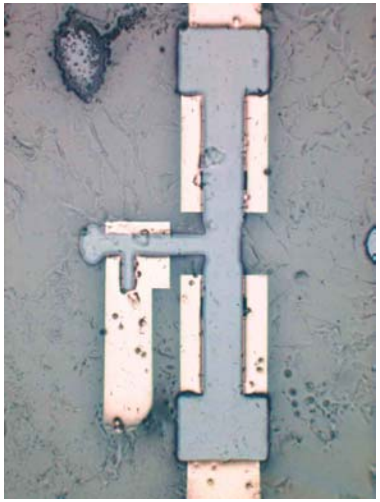


d) Remove Handle Wafer and Pattern

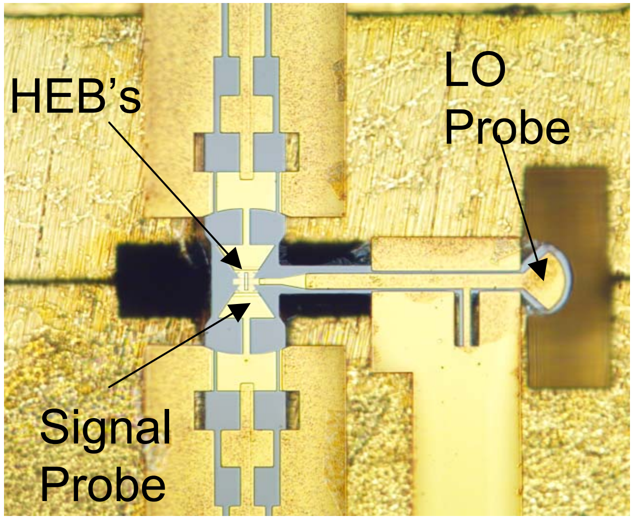


Back side etching of the silicon membranes – the chips are stuck in wax.





1.5 THz cross-bar balanced mixer hardware

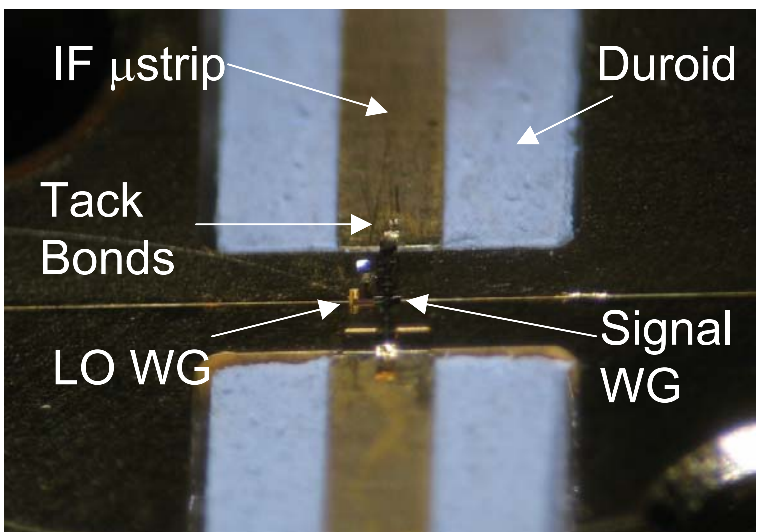


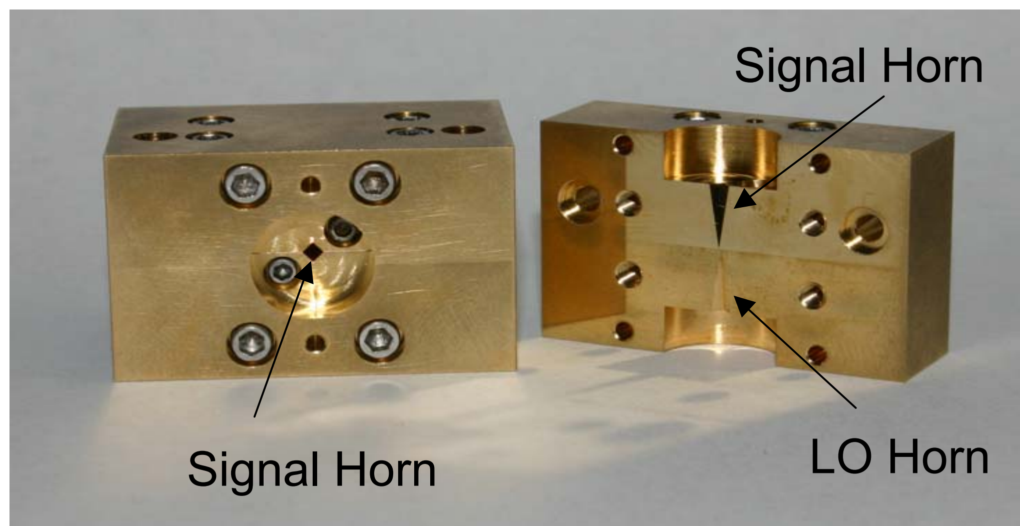
Chip in the Block

Chip Tack-Bonded to Block and Wiring

Block with LO and Signal Focusing Mirrors

Block External View

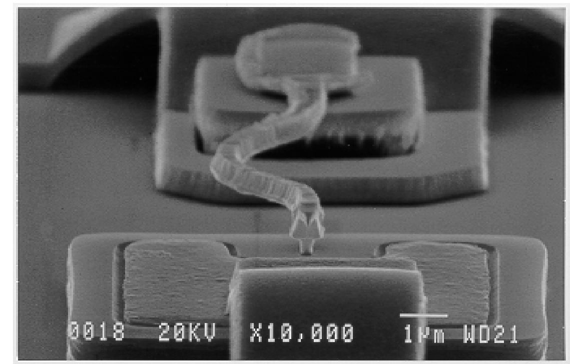




Summary of various mixer technologies

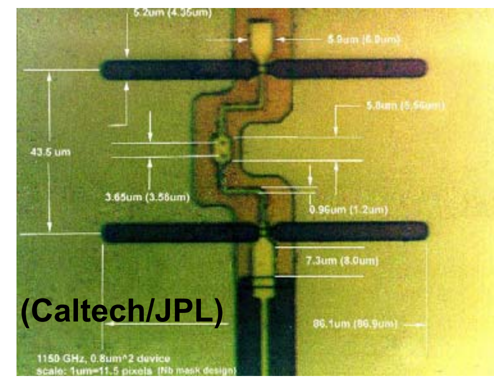
Schottky Diodes:

Works up to many THz.
Cooled or uncooled.
Noise 1700 K DSB @ 640 GHz
LO power 0.3-1 mW
Array applications in Atmospheric analysis, Security



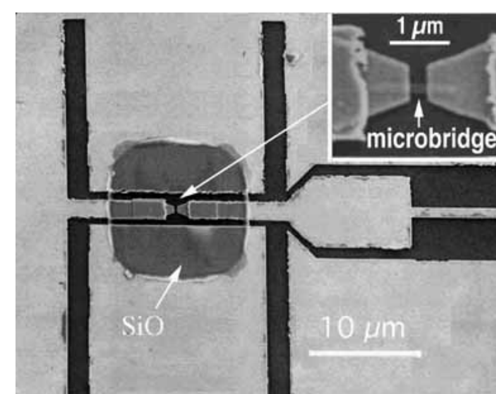
SIS:

Noise 80 K @ 500 GHz.
LO power about 50 microW.
Numerous array applications in astronomy up to 1400 GHz.



HEB:

Works up to at least 5 THz.
Receiver noise @ 500 GHz: ≈ 600K.
LO power 1 microW
Applications in astrophysics.



THz Frequency Sources

Need: Frequency coverage, frequency tuna-bility, robustness, frequency stability, Non-cryogenic functionality, spectral purity…

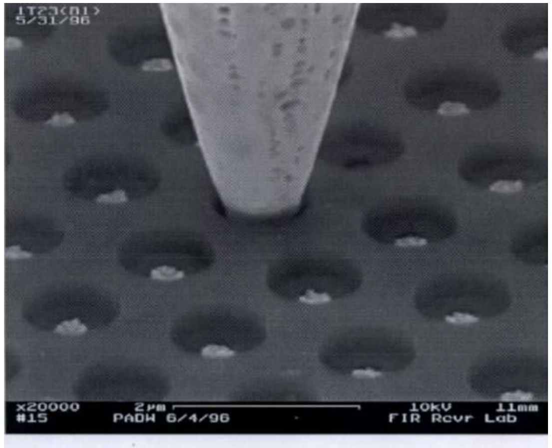
Schottky diode multipliers:

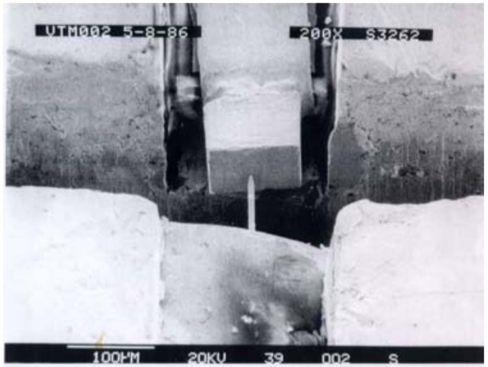
- Extremely small anodes
- Multiple anodes per chip
- Integrated with RF circuitry
- Testable
- Package-able

How to make THz diodes??

Long, long ago…

Whisker contacted anode

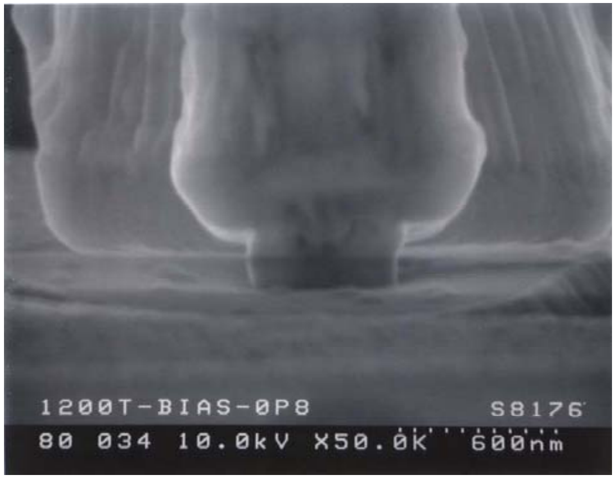


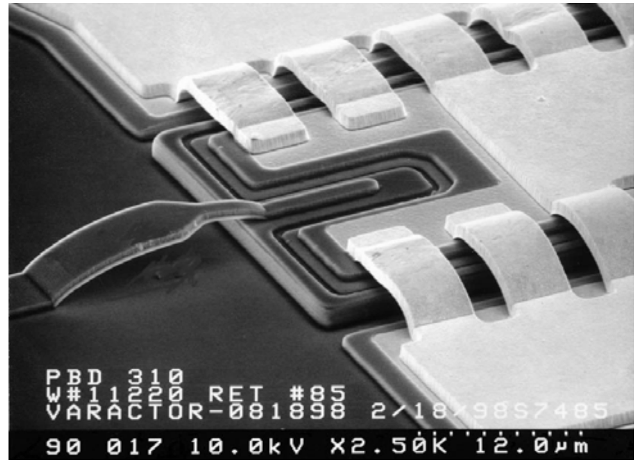


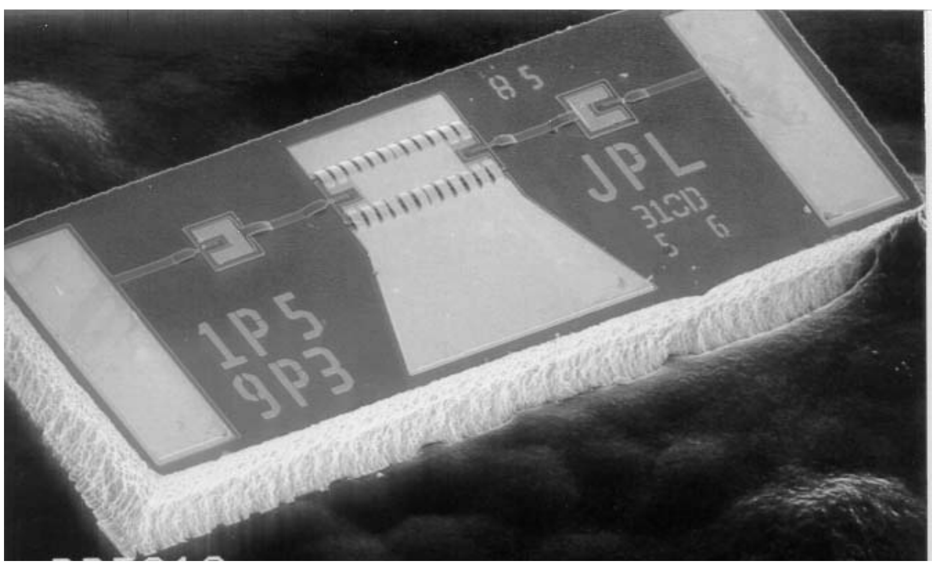
Planar diodes needed for:

- Robustness
- Increased functionality
- Increased reliability
- Increased repeatability
- High power handling
- Harmonic control

JPL Planar Schottky diodes



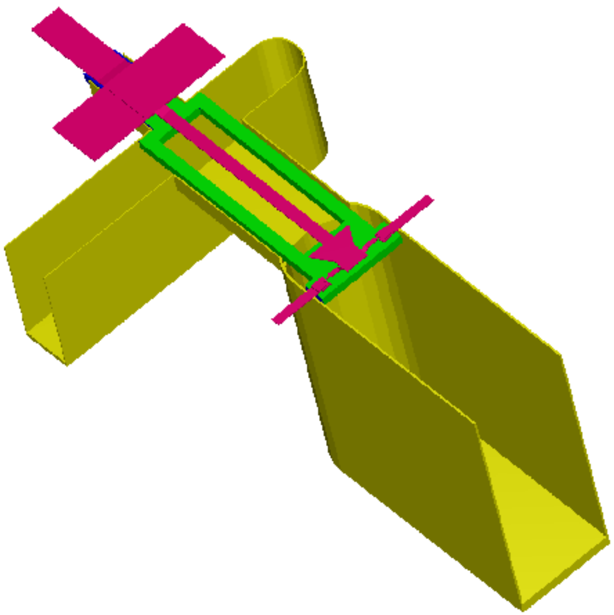


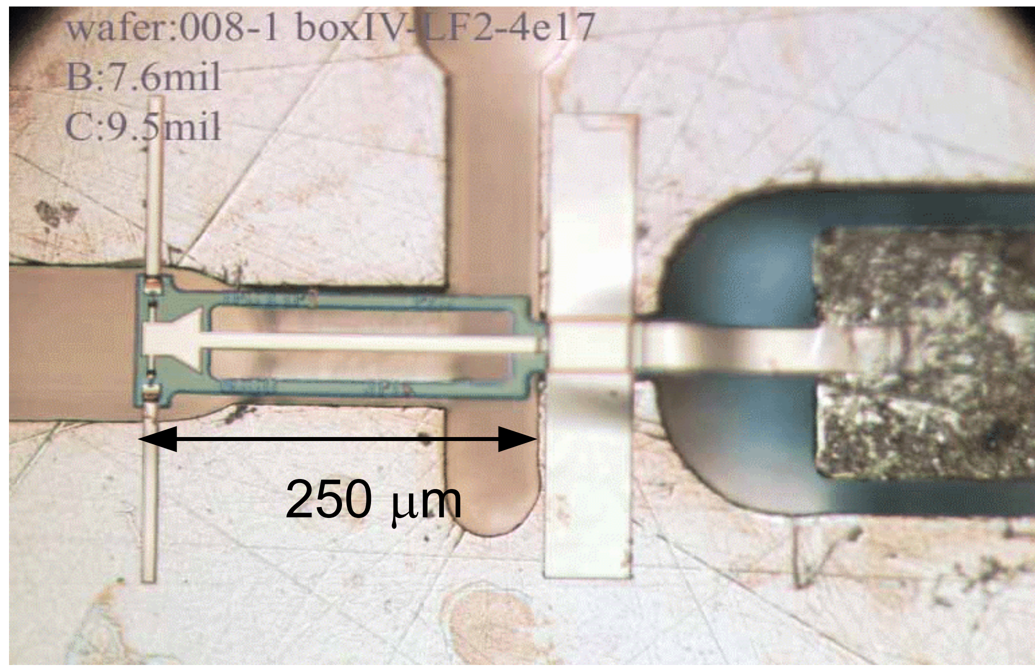


- Based on a proprietary planarization process that allows for
  - Self aligned anode and finger
  - Dry etching
  - No use of polyimide etc
  - E-beam compatible for real small anodes
  - T-gate like anodes

Substrateless Technology

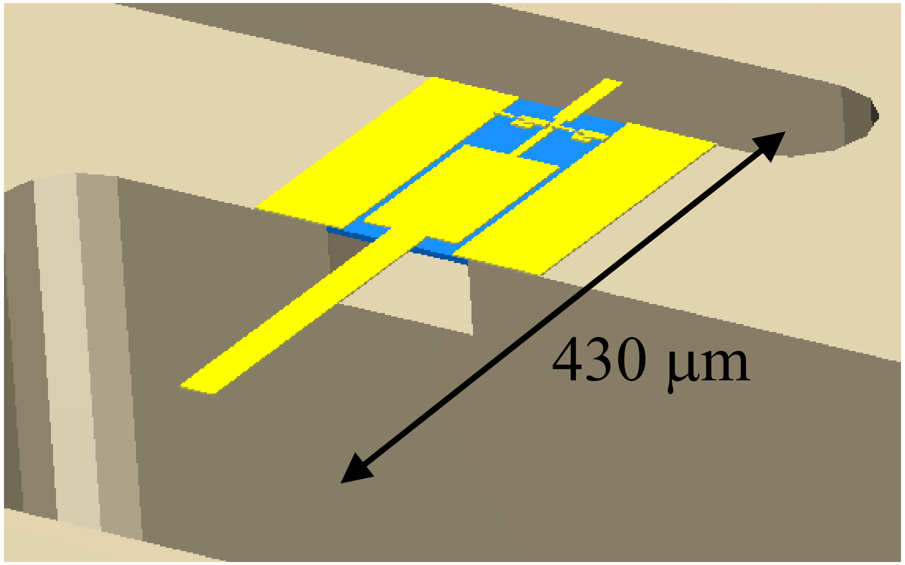
Remove substrate completely where not needed—substrate sculpturing

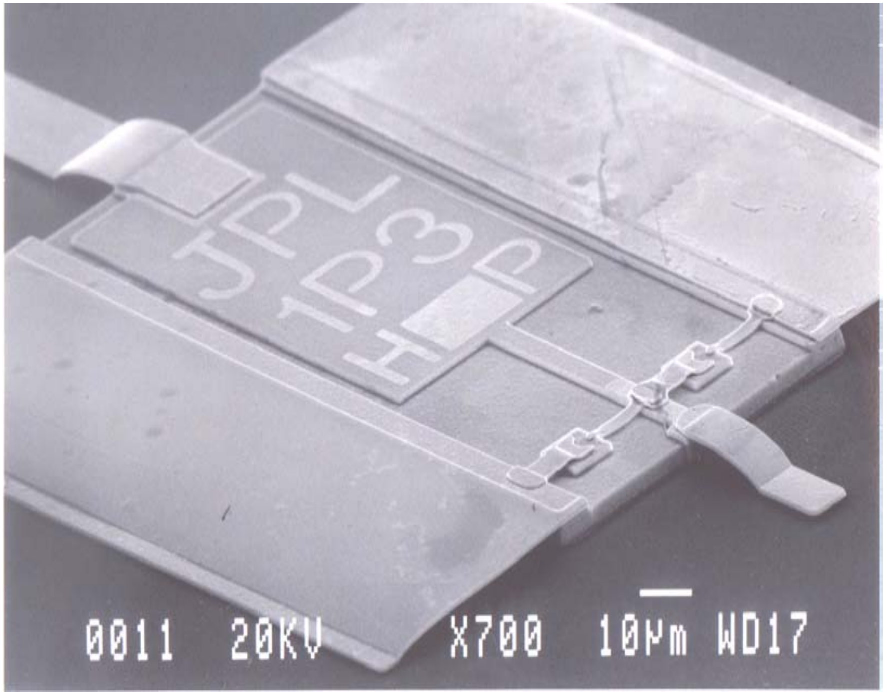




Devices beyond 1 THz

Solution: remove most of the GaAs substrate→membrane devices





1200 GHz tripler chip

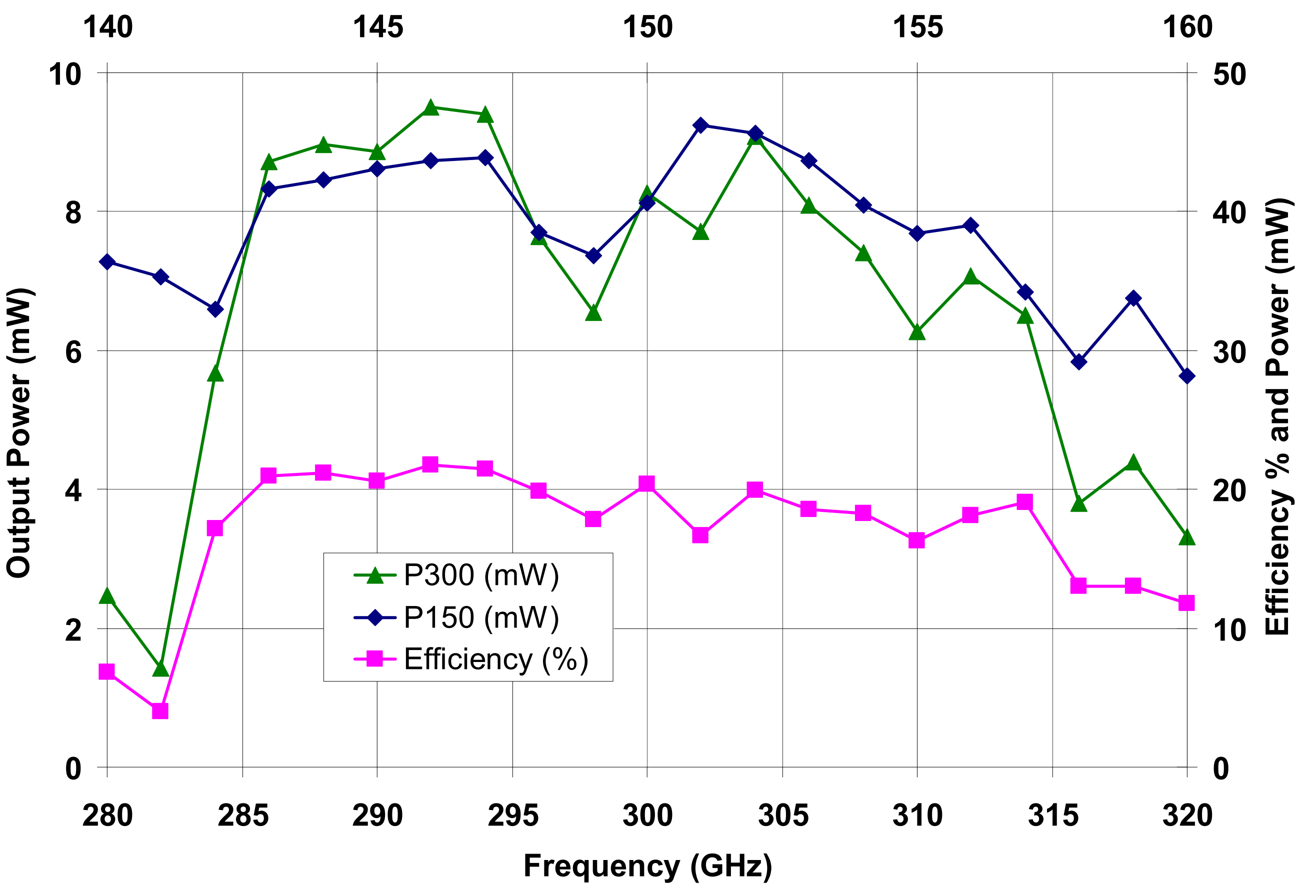
- **Membrane is 3 microns thick**
- **Extensive use of beam-leads**
- **Extremely simplified assembly**
- **Bias less design**

Robust process—scalable

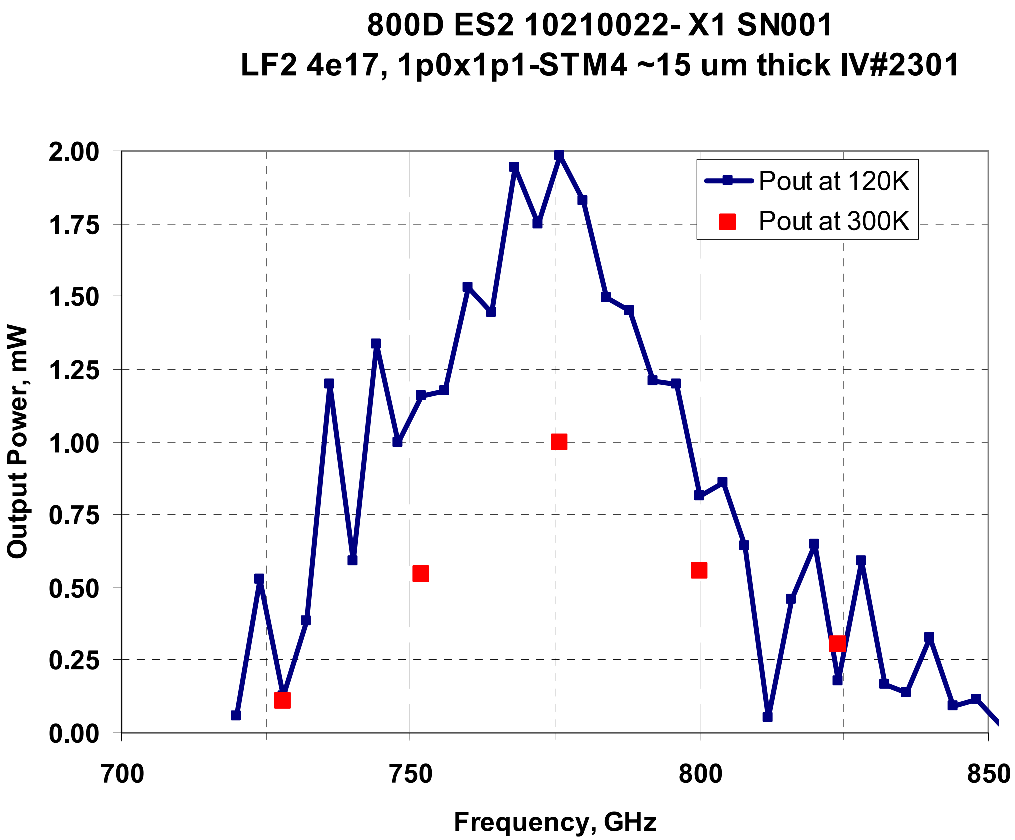
x2x2 Chain to 300 GHz

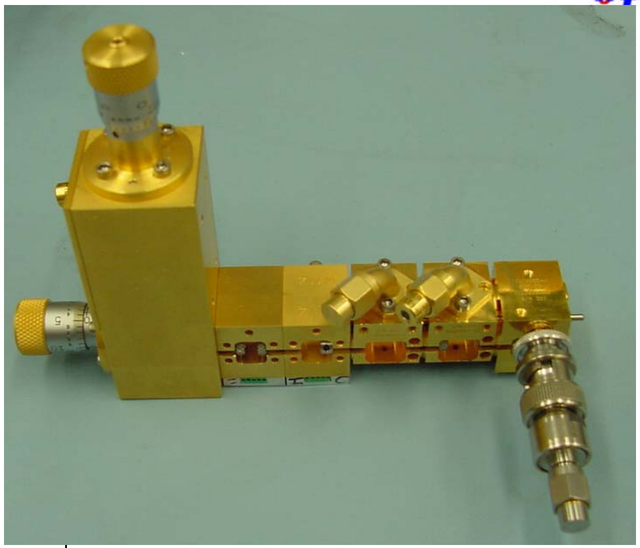
150 GHz Doubler
- 6 anodes in balanced configuration
- 10^{17} cm^{-3}

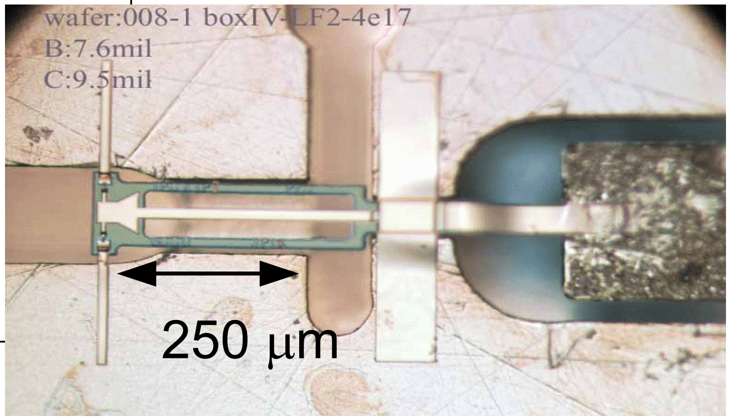
300 GHz Doubler
- 4 anodes in balanced configuration
- 10^{17} cm^{-3}



x2x2x2 Chain to 800 GHz

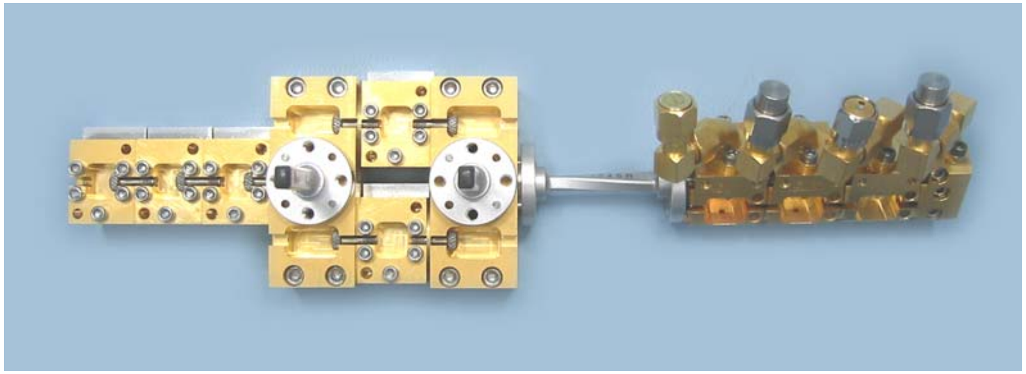


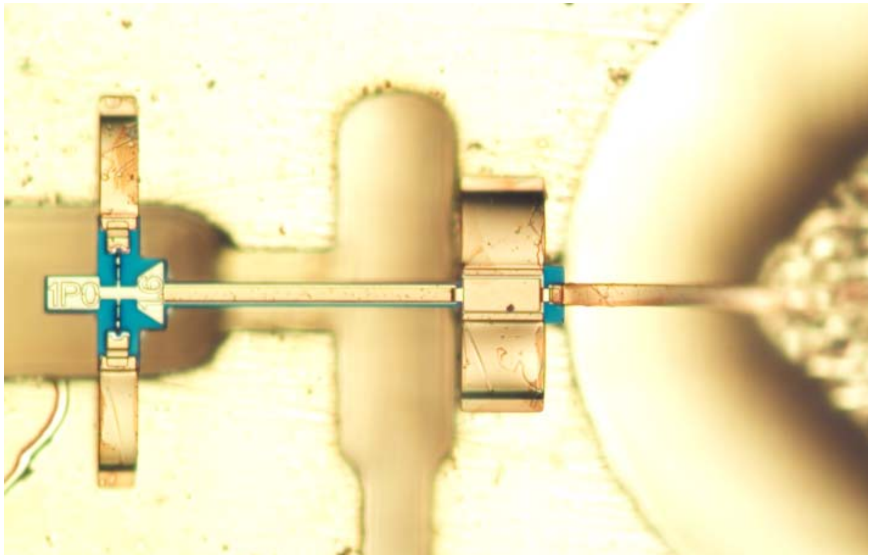


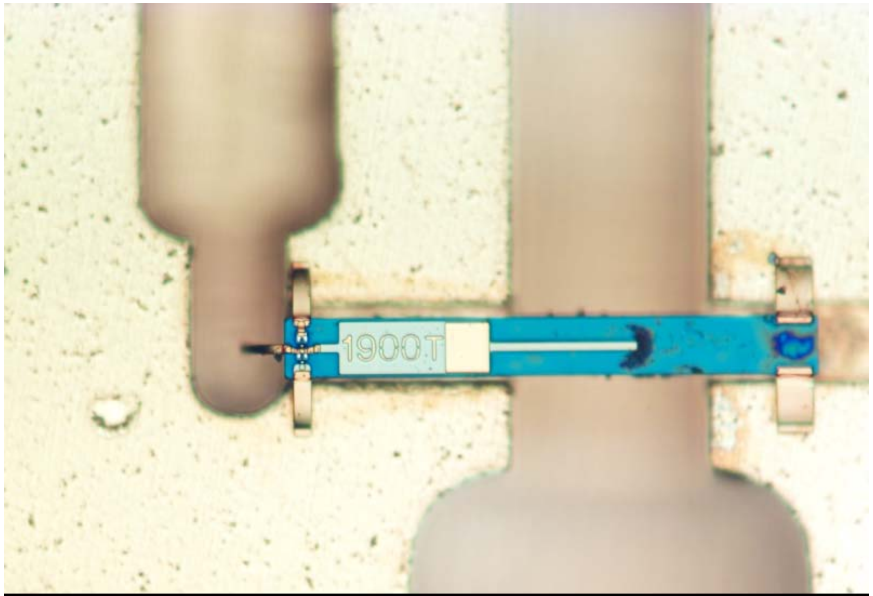


- At 120K peak power of 2mW, 3dB BW of >6%

1.4 – 1.6 THz Configuration







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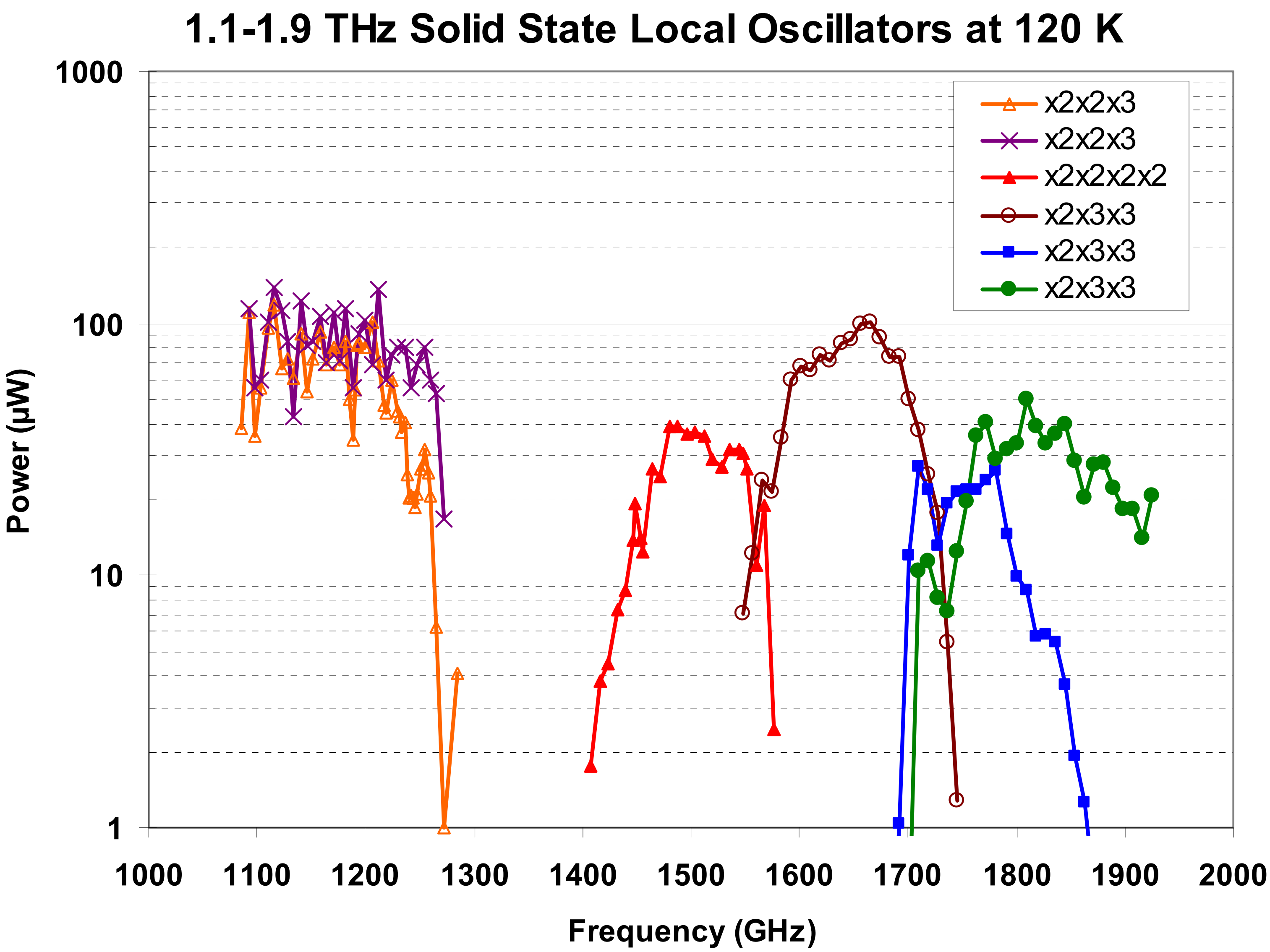
State-of-the-art



Possibilities for THz LO Sources in Space

	Freq Limit (GHz)	Output power	BW (%) Instant.	Efficiency (DC pwr)	Mass	Comments
2-Terminal Oscillators	~300	~mW	**<<1**	decent	small	Tuning nec., PLL, vendors?
Amplifiers	**~300**	mW--W	~10%	decent	small	Industrial support, developing tech.
BWO	>1 THz	good	**low**	**Very low**	**large**	Multimode, vendors
FIR lasers	>> 1 THz	high	**very narrow**	**low**	**large**	Useful for lab
QCLs	>>1.5 THz	high	**narrow**	decent?	medium	**Cryogenic**, lockable?, maturing fast
Multipliers	~3 THz?	mW--nW	~10-15%	low	small	Space heritage

Challenges going forward…

- Large pixel count focal plane arrays
- Schottky based receivers above 2.5 THz
- Robust tunable sources in the THz range
- Simple receiver architectures
- Efficient distribution of LO power
- Bandwidth
- Programmatic: Cost sharing strategies

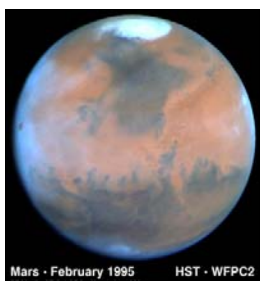
Current & Proposed THz Heterodyne Progs. at JPL

SPACE SCIENCE

KAO
Herschel HIFI
SOFIA
FILM
SAFIR

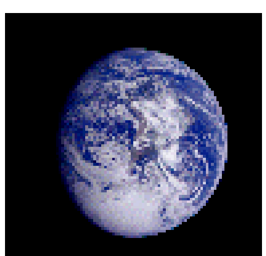
PLANETS

Rosetta MIRO
Marvel SIGNAL
Vesper SLS
TOAM



EARTH

UARS MLS
Aura MLS
SMLS



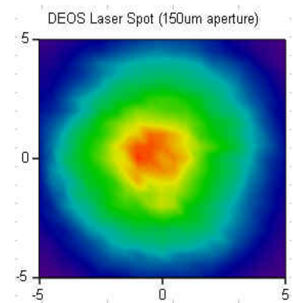
N A S A   O N L Y

C O S T   S H A R I N G

DoD

THz Biohazard
TH Radar
THz Comm.

NSF/SBIR



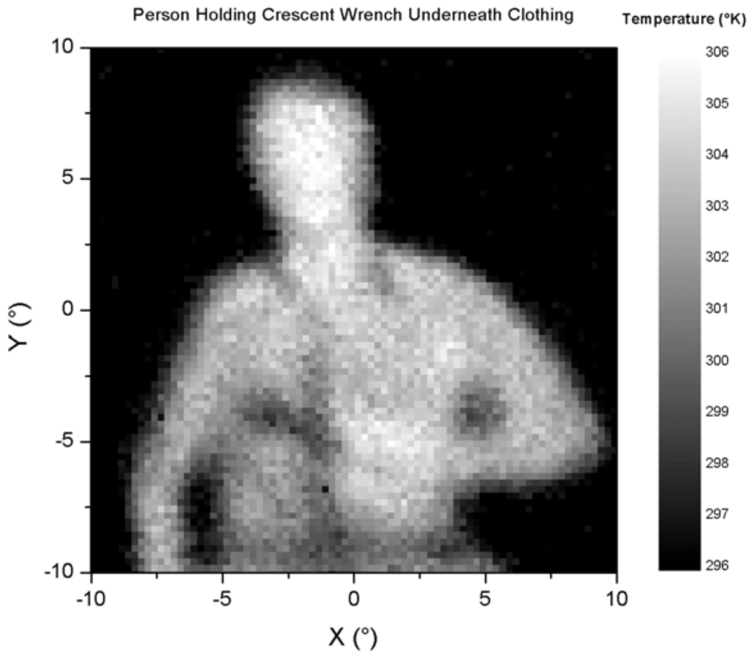
THz Gas Identification
THz MMIC’s

NIH

THz imaging
THz medical diagnostics

Applications:
Detection of hidden weapons or contraband.
Non-invasive inspection.
Spectroscopy of gases, aerosols or solids.

Modes:
Passive detection.
Active illumination.
Chirped for scanning or ranging.



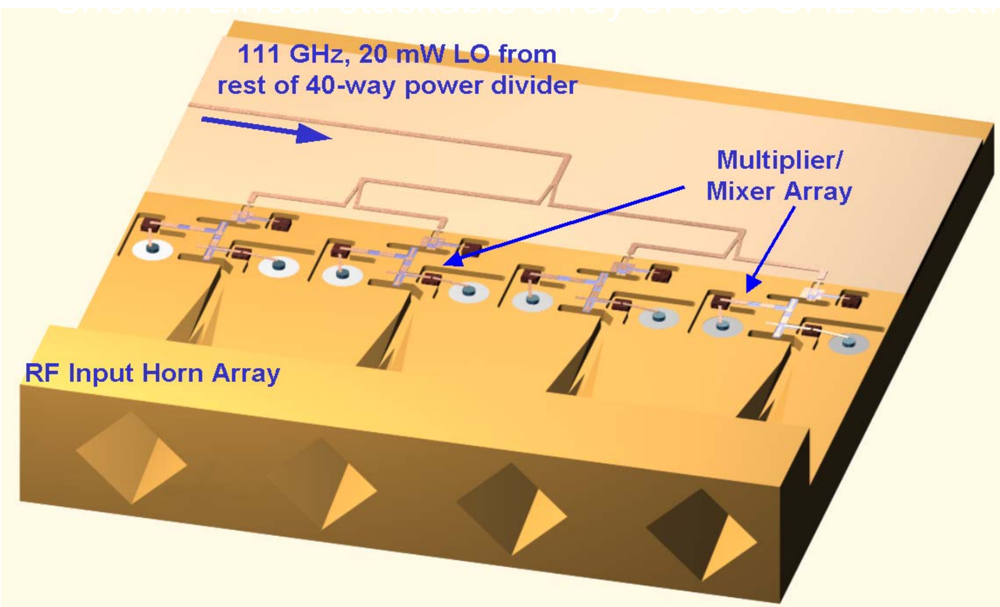
Passive 640 GHz heterodyne image of wrench hidden under shirt, with 10msec integration per pixel (scanned single pixel Schottky).

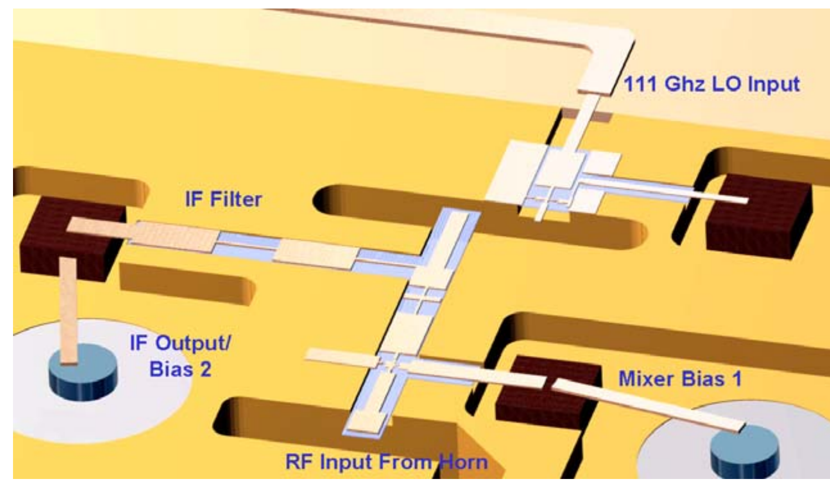
Focal Plane Array using Waveguide Technology

Conceptual idea: Include most functionality directly into each channel, so that the design can be replicated to a large array without system complications.

Waveguide design: Eliminates most RF and IF cross-talk between channels. High beam quality and polarization properties. LO injection does not require complicated optics. Easy boresighting on all channels.

Difficulties: Micromachining circuits above 1 THz. Uniform LO distribution.





For SIS/HEB : Added functionality (sideband separation) – "ultimate receiver" concept.
For THz HEB : Fundamentally pumped. Cross-bar balanced mixers for LO injection.

THz Imaging for Biomedical Applications: NIH

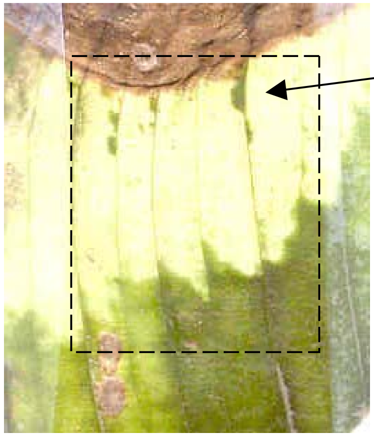
DESCRIPTION:
Application of NASA developed THz heterodyne sensor technology to THz Imaging for space science and biotechnology (joint NASA/NIH program)

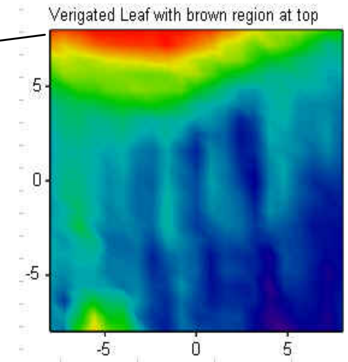
PRODUCT FUNCTION:
- Provides first ever THz images obtained by high spectral resolution, high sensitivity, ultra wide dynamic range heterodyne system.
- Utilizes both magnitude and phase information to yield tomographic style images of 3D objects
- Simultaneously measures absorption and reflection
- Links NASA and NIH through bio-applications
- >1000 times the penetrating power of existing T-Ray imagers in bio and other material samples

UNDERLYING TECHNOLOGIES:
THz semiconductor downconverters, far IR lasers/sources, new image construction and enhancement software

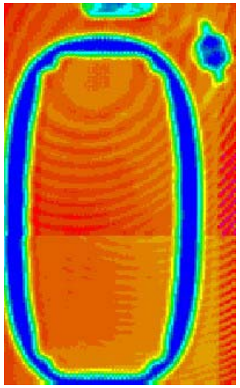
POTENTIAL USES:
Characterization of new and existing materials/structures
Multipixel imaging for greater signal throughput
Contrast mechanisms in disease diagnosis/material defects

CURRENT STATUS:
Initial “proof of concept” direct detection system established to get familiar with issues & capabilities
Heterodyne system assembled and in early testing phase



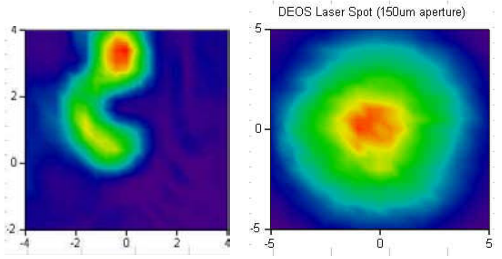


THz image of leaf



THz image of a JPL ID badge showing embedded RF coil and transceiver chip for electronic access. The interference pattern is likely Newton rings do to badge curvature.

THz image of DEOS far IR laser beam used to collect data above, before (left) and after (right) proper alignment by Eric Mueller of DEOS.



Summary

• High frequency (THz) heterodyne receivers are necessary

> To study origin of the basic materials of life in the star and planet forming environment

> To understand the physical & chemical state and motions of interstellar material in nearby galaxies and the Milky Way

> "Pretty pictures" alone will not answer some of our most basic questions

• Future THz heterodyne receiver needs

> Compact, low noise & power consumption, high power output LOs (Goal: 5 THz)

> Low noise mixers at higher frequencies in array format (Goal: arrays of 10's)

> Waveguide technology should enable compact focal plane arrays of Schottky, SIS and/or HEB mixers from a few hundred GHz to several THz

> Future detector arrays will be determined by the detector type, LO power (& funding source!!)